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Influence of velocity on horse and rider movement and resulting saddle forces at walk and trot

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RESEARCH ARTICLE

Abstract

To investigate the effect of increasing velocity within one gait on horse and rider movement and to describe the resulting changes in saddle forces, seven ridden dressage horses were examined on an instrumented treadmill. The speed ranged between 1.3-1.8 m/s at walk and 2.6-3.6 m/s at trot. Kinematics of the horse and rider, vertical ground reaction forces and saddle forces were measured simultaneously. Velocity dependency of each variable was assessed for the whole group with linear regression. With increasing velocity, the saddle forces at walk were mainly influenced by the accentuated rocking type of movement and at trot by the higher vertical dynamic and a more rigid horseback which resulted in increased counteracting force between horse and rider. Even small increases of velocity changed the dynamics of the movement pattern of the horse and consequently the forces emerging beneath the saddle: a 10% increase within the indicated speed range resulted in +5% (walk) and +14% (trot) higher total saddle force peaks. Accurate comparison of saddle forces requires speed-matched trials; velocity is therefore a factor which also has to be considered under clinical conditions.

Keywords: ground reaction forces, instrumented treadmill, kinematics, saddle pressure measurements, velocity dependency

1. Introduction

The velocity at which a subject is moving within each gait has a fundamental influence on numerous biomechanical variables. In horses, several authors focused their studies on speed-dependent changes in kinetic and kinematic variables and found that increasing velocity reduces stride duration and extends stride length (Clayton, 1994, 1995; Dusek *et al.*, 1970; Leach and Drevemo, 1991) and although limb impulses decrease, peak vertical forces increase as a result of reduced relative stance durations (Khumsap *et al.*, 2001a; McLaughlin *et al.*, 1996; Weishaupt *et al.*, 2010). Knowledge of the mathematical functions of these changes enables comparison of individual gait patterns studied at different velocities. On the treadmill, stride duration, stride length and limb impulses change in a linear fashion with increasing velocity, whereas relative stance and suspension duration, as well as peak vertical forces change exponentially (Weishaupt *et al.* 2010). Khumsap *et al.* (2001b, 2002) utilised net moment and power of fore- and hindlimb joints to relate ground reaction forces to muscle function and found that with increasing velocity peak moments and power in the joints of the hindlimbs increased, providing more forward propulsion. In the forelimb joints, only minimal velocity-dependent changes in net joint energies occurred, indicating that, compared to the hindlimbs, adjustments in muscle activity did not behave in the same way. Increasing velocity also influences back movement. In unridden horses at trot, a reduced flexion-extension movement of the back was observed caused by increased muscle activity of the trunk muscles (Robert *et al.* 2001a,b, 2002). However, there is no information as to how the movement of the horse's back adapt to increasing velocities at walk. Byström *et al.* (2009, 2010) investigated the kinematics of saddle and rider with horses walking and trotting on a treadmill and showed that saddle and rider follow a common movement pattern which clearly originates from the horse's movement: at walk rider movements were related to the alternating level difference between the horse's croup and withers whereas at the trot vertical and horizontal de- and acceleration of the horse's trunk had the greatest effect on the riders movement.

Saddle pressure distribution and saddle force curve pattern are reported to be characteristic for each gait: at walk the force curve showed four (Fruehwirth *et al.*, 2004; Winkelmayr *et al.*, 2006), in more recent investigations six minimum and maximum values per stride (Von Peinen *et al.*, 2009), whereas in the sitting trot a typically m-shaped curve with two maxima and minima was observed (Fruehwirth *et al.*, 2004; Peham *et al.*, 2008; Winkelmayr *et al.*, 2006). It is also known that riding style substantially influences the saddle force pattern within the same gait. In contrast to the seated canter, where the load is concentrated in the rear saddle half (Fruehwirth *et al.*, 2004; Winkelmayr *et al.*, 2006), riding in a two point jockey seat at canter and gallop leads to a concentration of the pressure predominantly in the front third of the saddle (Latif *et al.*, 2010). In a recent study on Icelandic horses, it was shown that the total saddle force curve of the tölt resembles that of trotting horses (Ramseier *et al.* 2013).

The velocity dependency of kinetic and kinematic variables and the strong interrelationship between movement pattern of horse and rider suggest that saddle pressure also is influenced by velocity. Therefore, controlling speed may be decisive when conducting repeated measurements of the same subject or when measurements of different subjects need to be compared with each other. When carrying out saddle pressure measurements in daily practice, the velocity chosen is often one which best suits the horse, the rider and the circumstances; speed measurements are rarely carried out. The influence of varying velocities while assessing a saddle, e.g. pre and post fitting/correction, is unknown.

The aim of this study was to describe the effect of increasing velocities within one gait on the interaction between horse and rider and the resulting saddle forces in order to assess its practical relevance. It was hypothesised that even small changes in subject velocity would significantly influence the interplay between horse and rider and therefore the saddle forces.

2. Materials and methods

Experimental setup

Kinematic, kinetic and saddle pressure data of seven high level dressage horses (mean ± standard deviation: age 14±4.3 years, height at the withers 1.70±0.07 m, body mass 609±62 kg) which were part of another study (Von Peinen *et al.*, 2009; Weishaupt *et al.*, 2006) were analysed retrospectively with regards to velocity dependency of saddle pressure variables. The horses were carefully adapted to treadmill locomotion and were ridden by their own professional riders using their usual tack. Horses were ridden with the neck raised, the poll high and the bridge of the nose slightly in front of the vertical in walk and sitting trot. Treadmill speed was varied between 1.3 and 1.8 m/s in increments of 0.1 m/s at walk and between 2.6 and 3.6 m/s in increments of 0.2 m/s at trot. This resulted in four to five measurements per gait and horse. Accuracy of treadmill belt velocity was ±0.8% at 3.5 m/s). The experimental protocol was approved by the Animal Health and Welfare Commission of the Canton of Zürich, Switzerland (208/2004).

Data acquisition

Vertical ground reaction forces (FG) and related time variables were measured with an instrumented treadmill (TiF; Weishaupt *et al.*, 2002). Saddle pressure was measured with a Pliance-X system (Novel GmbH, Munich, Germany) using a sensor mat (2 mat parts, 16×8 (longitudinal × transverse) sensors each, sensor size 4.7×3.1 cm) calibrated prior to the experiment (Von Peinen *et al.*, 2009). The two mat parts were placed symmetrically on each side of the horses back, leaving a gap along the spine. Zero baseline was established before saddling and tightening the girth. For the kinematic analysis, spherical infra-red reflective markers (diameter 19 mm) were placed over the following anatomic landmarks: (1) horse: cranial border of the left wing of the atlas, spinous processes of T6, L3, S3, midpoint between the *tuber spinae scapulae* and the shoulder joints (shoulder), left and right *tuber coxae* (hip), and lateral wall of the left front and hind hoof; (2) rider: sacrum; (3) saddle: left and right buttons at the pommel (saddle front), and on both sides at the caudal ends of the panels (saddle hind). The markers were recorded with 12 infrared cameras (ProReflex®, Qualysis, Gothenburg, Sweden) and their xyz-coordinates calculated with Qualisys Track Manager software. The right-handed coordinate system was aligned with the treadmill, with the x-axis pointing in direction of the horse's head and the z-axis upwards. Synchronised recordings of 10 s were made with the three measuring systems. Depending on the actual viewing condition, a cameras frame rate of 140 Hz or 240 Hz was chosen; accordingly, integer rates of sampling frequencies for the Pliance-X system (70 Hz or 60 Hz) and the TiF system (420 Hz or 480 Hz) were used (Von Peinen *et al.*, 2009).

Data analysis and statistics

Time series of kinetic, kinematic and saddle force data as well as the limb contact times extracted from TiF software (HP2; University of Zürich, Zürich, Switzerland) were imported into MatLab (The Math Works Inc., Natick, Massachusetts, USA) for data processing. Based on forelimb toe-on times, time series of each record were split into strides, which then were time-standardised to 101 points (0 to 100% stride duration, SD); all standardised strides of a record were averaged. Of this averaged standardised stride, discrete values such as the stride-mean (Smean, mean value during entire stride), the magnitude of extremes (minimum, maximum), and if appropriate the range of movement (ROM), as well as values for specific time points, were determined for respective variables. In general, all time variables within a stride were expressed relative to SD (%SD). FG data were additionally standardised to the combined horse and rider weight (HRW) as N/N and expressed as percentage of this weight (%HRW); the respective impulses were standardised accordingly to N/N s (%HRW s). For each limb, peak and minimum forces were determined (walk: FG P1, FG P2, FG M; trot: FG P). Saddle pressure data were converted into saddle force values (FS) and standardised to the combined weight of the rider, saddle and instrumentation (%RW). Both weights were determined from the respective force data intrinsically (Von Peinen *et al.*, 2009). As walk and trot are symmetrical gaits, the movements of a sound horse and rider are similar for the two half-cycles, merely phase-shifted by 50% of stride. This allowed the pooling of corresponding amplitude and time values, reducing the amount of data and facilitating interpretation. Time points within the first half-cycle referred to the first contact of the left forelimb (LF), the ones of the second half-cycle to first contact of the right forelimb (RF). The saddle forces of the entire mat (FS_{tot}) were calculated as well as of the left and right halves individually. Additionally, 3 transverse sections of the pressurised area of the saddle mat halves were determined mathematically (FS_{front}, FS_{mid}, FS_{hind}). Each sector occupied 1/3 of the maximal longitudinal extent of the loaded sensor area; accordingly, 6 partial saddle forces could be distinguished. Discrete values were determined from the stride standardised partial saddle force curves: (1) saddle force Smean, representing the mean proportion of the rider's weight within the respective sector, (2) the magnitudes of the local maxima (walk: P1, P2, P3; trot: P) and local minima (walk: M1, M2, M3, trot: M) and (3) the respective time points of the maxima and minima (Figure 1). Numerous kinematic variables were derived from one or more marker data. Rotation angles (shoulder, hip) referred to the axis indicated and were positive for clockwise rotation if the horse was seen from behind (x-rotation) and from above (z-rotation). Additionally, the following angels were calculated in the sagittal plane: neck angle (atlas-T6-S3), flexion-extension angle of the back (T6-L3-S3), back inclination angle (T6 with reference to a horizontal line through S3; positive if T6>S3), and pro-retraction angles of the fore- (hoof-shoulder) as well as of the hindlimbs (hoof-hip).

Investigation of velocity dependency was based on 'mean-normalised data'; i.e. for each variable, gait and horse the mean value over the full range of velocities was calculated and the velocity-dependent changes were expressed as delta values to that variable's mean. Respective delta velocities were calculated in the same way. For each variable, the 'mean-normalised data' of all horses were subject of a least square regression analysis in MS Excel (Microsoft Corp., Redmond, WA, USA). This procedure enabled the investigation of the velocity dependency regardless of the individual levels of the absolute data. If the probability for the regression slope (b) was $P<0.05$ a velocity dependency was accepted. A group mean (Gmean) and a respective group standard deviation were calculated from the individual mean values.

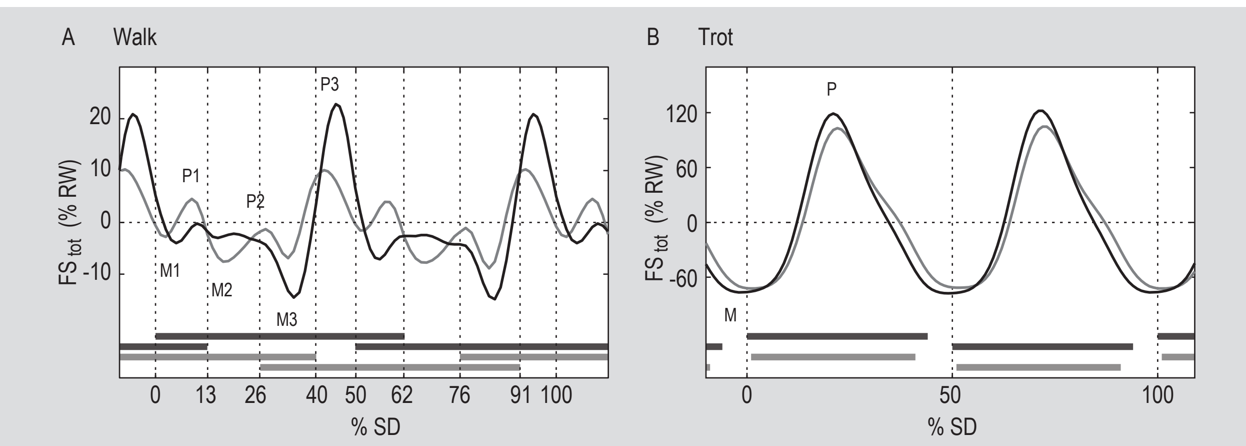

Figure 1. Mean total saddle force curves (FS_{tot}) for all horses (n=7) during one stride cycle (0-100% stride duration (SD)). Forces varied around the stride mean force, which was equal to the rider's weight (RW); variations were expressed as percentage of %RW. The grey curve shows the group mean at the slowest and black at the fastest velocities. Bottom: traces of limb footfall pattern, from top to bottom LF, RF, LH and RH, dividing the stride cycle by first contact RF into two half-cycles. (A) At walk the half-cycle was divided into 4 phases by first contact and toe-off of the limbs. FS_{tot} M1 and P1 occurred within the first phase, M2 within the second phase, P2 coincided with the end of the second phase, M3 occurred in the third phase and P3 in the fourth phase. (B) At trot the maximum (P) occurred during each diagonal stance phase and the minimum (M) during the suspension phase.

3. Results

Walk

Gmean velocity (± standard deviation) was 1.57±0.06 m/s. Velocity of individual horses altered on average by ±9.3% around the horse's mean velocity. Speed-dependent changes of selected ground reaction force, kinematic and saddle force variables are listed in Table 1. With increasing velocity both SL and SF increased; however, the percentage by which each horse altered its SL and SF varied considerably between individuals. If considered as a group, the relative lengthening of SL contributed by 57% and the increase of SF by 43% to the horses' response to faster velocities. SD, stride impulse (IS), as well as relative stance duration (StD) decreased with increasing velocity, whereas the distribution between fore- and hindlimb impulses remained unchanged. In the forelimbs only the second FG peak (P2) increased whereas in the hindlimbs both, FG P1 and FG P2 increased. With faster walking speeds, the ROM of the pro-retraction angle increased in all limbs. In the forelimbs this increase was associated with an increase of the z-rotation of the shoulders. The periodical head nodding (vertical ROM) increased distinctly and the time point at which the head reached its lowest position coincided with the FS_{tot} M3 minimum. Simultaneously, the x-distance of T6 to the saddle front reached a maximum; horizontal ROM of the latter increased as well with increasing velocity. With regard to the horse's topline, the vertical ROM of L3 and S3 increased more than the ROM of T6. Additionally, vertical movement of T6 and L3/S3 were 50% phase shifted; T6 was highest and L3/S3 lowest, both, again exactly at time of FS_{tot} M3, which resulted in an enlarged ROM of back inclination (Figure 2). Concomitantly, the z-distance between the rider sacrum and saddle hind was maximal and its ROM during the stride increased with speed. At low velocities, in FS_{tot} up to 3 minima (M1 to M3) and maxima (P1 to P3) could be distinguished for each half of the stride cycle (Figure 1A). With increasing velocity, FS_{tot} became less complex; the consistent local extremes (M3, P3) strongly developed with increasing velocity (Figure 1A, 2). Regarding the partial saddle forces at the time point of FS_{tot} M3, mainly FS_{front} and to a lesser extent FS_{hind} decreased in both, the left and right side of the saddle (Figure 3). At time of FS_{tot} P3, FS_{front} and FS_{mid} significantly increased, but only on the side where the forelimb was in the final phase of protraction. With faster speeds, the rider weight was re-distributed to the central section at the expense of the hind section.

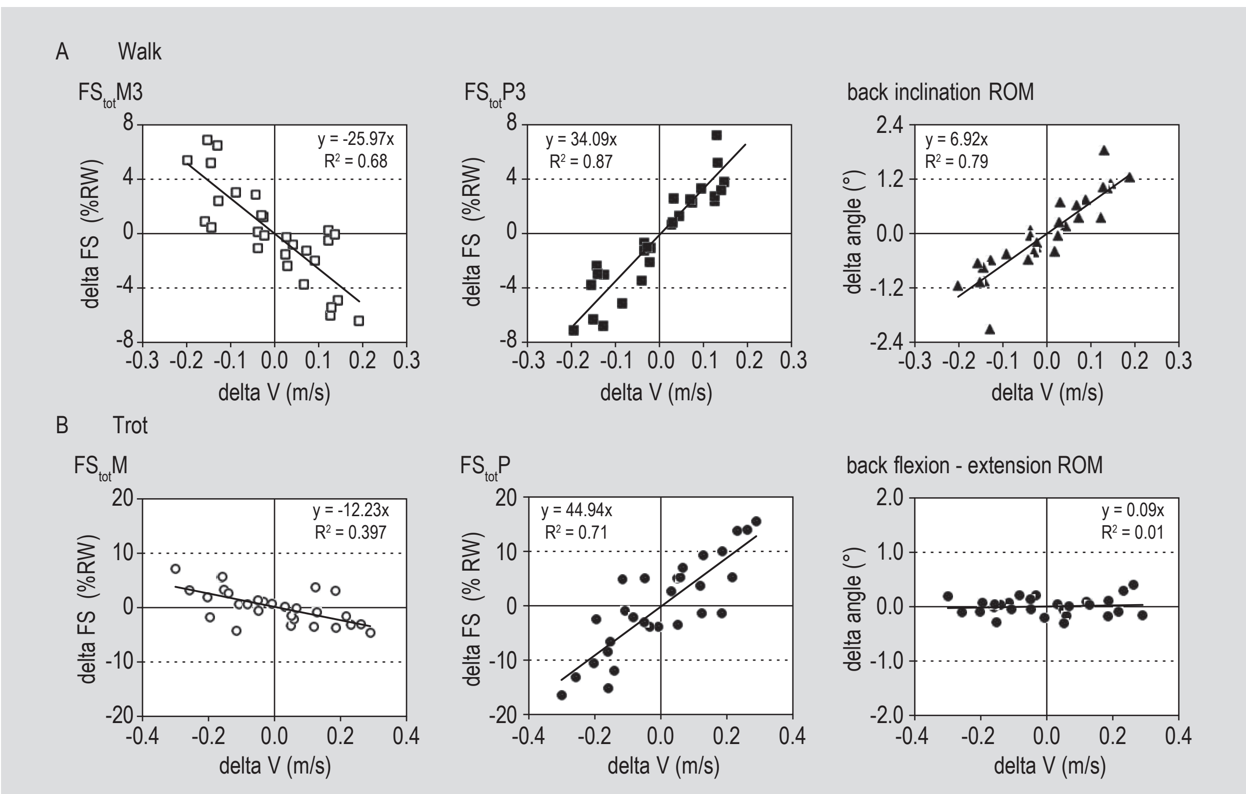

Figure 2. Velocity dependencies of total saddle force extremes (FS_{tot} M (minimum) and P (peak)) and kinematic back movement variables at (A) walk and (B) trot. The variables are delta to the respective mean value, which are listed together with the respective regression coefficients in Tables 1 and 2. Back inclination: angle of T6 with reference to a horizontal line through S3; its range of movement during a stride (ROM) represents the rocking movement at walk. Back flexion-extension: ROM of the angle between T6-L3-S3 did not change despite the increased vertical dynamics at higher trotting velocities.

Table 1. Walk: velocity dependency of ground reaction force, kinematic and saddle force variables[1].

	Variable[2]	Type[3]	Unit[4]	Gmean	b	r²	p
Gait characteristics	SD	value	s	1.147±0.047	-0.321	0.82	<0.01
	SF	value	s^{-1}	0.874±0.037	0.246	0.81	<0.01
	SL	value	m	1.793±0.093	0.656	0.88	<0.01
	$StL_{forelimb}$	value	m	1.120±0.071	0.262	0.63	<0.01
	$StL_{hindlimb}$	value	m	1.148±0.034	0.332	0.82	<0.01
	$StD_{forelimb}$	value	%SD	62.5±1.3	-8.5	0.82	<0.01
	$StD_{hindlimb}$	value	%SD	64.1±1.5	-5	0.80	<0.01
	IS	value	%HRW s	114.7±4.7	-32.1	0.82	<0.01
Vertical ground reaction forces	$FG_{forelimb}$: P1	value	%HRW	62.6±2.5	2.5	0.06	0.18
	$FG_{forelimb}$: P2	value	%HRW	63.7±3.5	12.5	0.56	<0.01
	$FG_{hindlimb}$: P1	value	%HRW	41.9±2.1	19.8	0.89	<0.01
	$FG_{hindlimb}$: P2	value	%HRW	42.2±1.5	5.4	0.39	<0.01
Kinematic variables	Pro-retraction angle LF	ROM	degree	38.7±3.1	10.6	0.68	<0.01
	Pro-retraction angle LH	ROM	degree	40.0±1.5	12	0.82	<0.01
	Shoulder	x-rotation	degree	17.0±2.6	6.3	0.22	0.01
	Shoulder	z-rotation	degree	25.2±3.4	7.2	0.50	<0.01
	Hip	x-rotation	degree	9.3±1.7	7.9	0.69	<0.01
	Hip	z-rotation	degree	7.8±3.0	-0.3	0.00	0.73
	Neck angle (atlas-T6-S3)	ROM	degree	12.7±2.0	19.4	0.96	<0.01
	Atlas	z-ROM	mm	75±14	150	0.76	<0.01
	T6	z-ROM	mm	24±10	29	0.38	<0.01
	L3	z-ROM	mm	73±22	65	0.62	<0.01
	S3	z-ROM	mm	71±8	85	0.88	<0.01
	Back inclination angle (T6-S3)	ROM	degree	5.3±1.2	6.9	0.79	<0.01
	T6 – saddle front	x-Smean	mm	93±28	21	0.45	<0.01
	T6 – saddle front	x-ROM	mm	16.5±5.8	22	0.66	<0.01
	Rider sacrum – saddle hind	z-ROM	mm	36±11	44	0.53	<0.01
Saddle forces	FS_{front}	Smean	%RW	31.9±7.8	1.8	0.02	0.51
	FS_{mid}	Smean	%RW	38.7±2.7	5.9	0.47	<0.01
	FS_{hind}	Smean	%RW	29.4±7.2	-7.7	0.25	0.01
	FS_{tot}: M3	value	%RW	85.6±10.3	-26	0.68	<0.01
	FS_{front}: at time of FS_{tot} M3	value	%RW	20.5±5.7	-18.2	0.60	<0.01
	FS_{mid}: at time of FS_{tot} M3	value	%RW	37.6±4.3	1.1	0.01	0.58
	FS_{hind}: at time of FS_{tot} M3	value	%RW	27.5±7.3	-9	0.31	<0.01
	FS_{tot}: P3	value	%RW	120.8±10.4	34.1	0.87	<0.01
	FS_{front}: at time of FS_{tot} P3	value	%RW	35.3±8.2	16.2	0.41	<0.01
	FS_{mid}: at time of FS_{tot} P3	value	%RW	46.8±6.8	20.8	0.79	<0.01
	FS_{hind}: at time of FS_{tot} P3	value	%RW	38.8±11.5	-3	0.03	0.4

[1] Gmean: group mean values (± inter-subject standard deviation) of 7 horses at a mean walking velocity of 1.57±0.06 m/s; b: regression coefficient (slope) given as units/(m/s); r^2: coefficient of determination; p: probability of slope b.

[2] Variables: SD: stride duration; SF: stride frequency; SL: stride length; StL: stance length; StD: stance duration, IS: stride impulse; FG: vertical ground reaction force peaks (P1, P2); pro-retraction angle LF: rotation of left front hoof around mid-position of both shoulder markers; pro-retraction angle LH: rotation of left hind hoof around mid-position of both hip markers; back inclination angle: T6 with reference to a horizontal line through S3 (positive if T6>S3); FS: saddle force, of total saddle pressure mat (with minima M3 and peak P3, see Figure 3); FS_{front}, FS_{mid}, FS_{hind}: saddle forces in the frontal, mid and hind transversal saddle third; $FS_{(third)}$ at time of FS_{tot} M3 or P3: force at the respective saddle third contributing to FS_{tot} M3 or P3 magnitude, respectively.

[3] Type: value: discrete value; Smean: stride mean; ROM: range of motion; x: co-ordinate (towards head of horse); z: co-ordinate (upwards).

[4] Units: %SD: time as percentage of SD; %HRW: standardised to horse and rider weight (100 N/N); %RW: standardised to rider weight (100 N/N).

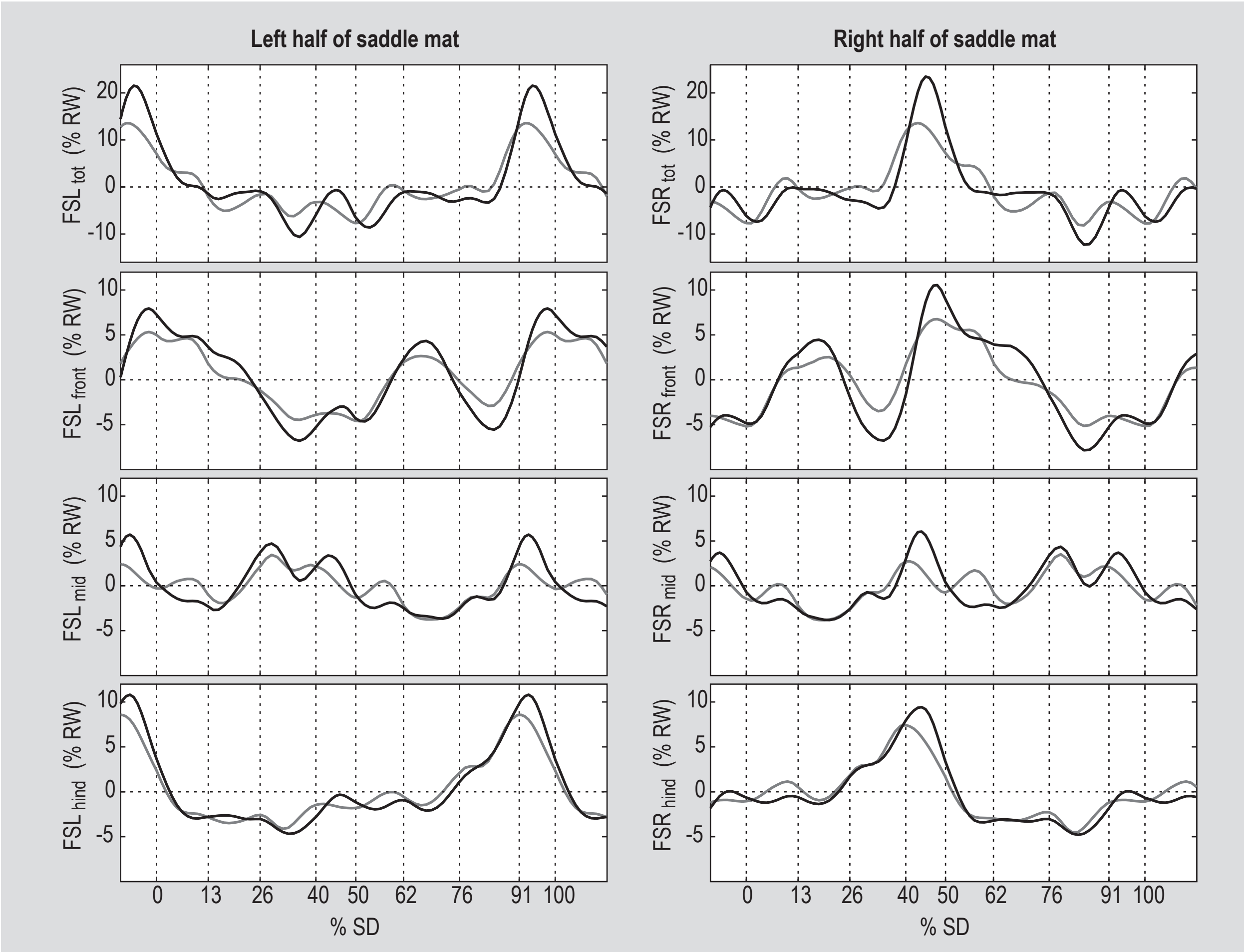

Figure 3. Mean saddle force curves (n=7) for the left and right half of the saddle pressure mat at walk (first row). Three transverse sections of equal length were determined from the total pressurised saddle area (FSL/R_{tot}), resulted in three partial saddle forces per mat half (row 2-4) at the front (FSL/R_{front}), mid (FSL/R_{mid}) and hind (FSL/R_{hind}) section, respectively. Forces varied around the stride mean of the respective sector; variations were expressed as percentage of rider weight (%RW). The grey curve shows the mean at the slowest and the black the mean at the fastest velocities during a standardised stride cycle (0-100% stride duration (SD)).

Trot

Gmean velocity was 3.05±0.08 m/s with a mean individual speed variation of ±6.9%. Speed dependencies of selected variables are listed in Table 2. Horses adapted to faster velocities predominantly by increasing their SL. The proportion by which SL and SF changed was similar for all horses and amounted to 79% for SL and 21% for SF. SD and as a result, IS decreased, whereas horses maintained a constant impulse distribution between fore- and hindlimbs. In all limbs relative StD decreased and FG peaks increased; as a consequence relative suspension duration became longer. The head nodding decreased, whereas only the ROM of S3 decreased when looking at the backline, resulting in a more homogeneous up- and downwards movement of the entire backline. Back flexion-extension angle (Smean T6-L3-S3 in sagittal plane) remained nearly unchanged and did not change its ROM with increasing velocity (Figure 2). Regarding FS_{tot}, the maximum (P) developed strongly (Figure 2); it occurred concomitantly to the time where downward movement of the horse was maximally decelerated, i.e. at time of FG_{tot} P (Figure 1B). In contrast, FS_{tot} M was reduced by a smaller extent. Both components were predominantly caused by alterations of FS_{mid}. Regardless of velocity, the mean rider weight distribution did not significantly change between the transversal sections.

3. Discussion

Von Peinen *et al.* (2009) found that at walk the horse's basic motion pattern had a formative influence on rider movement and thus on the saddle force pattern. Similarly at trot, the movements of the horse dictate the basic pattern of the rider's movements (Byström *et al.*, 2009). The present study demonstrated, that increasing velocity significantly accentuate the basic motion pattern of the respective gait and consequently exerted a distinct formative influence on

Table 2. Trot: Velocity dependency of ground reaction force, kinematic and saddle force variables[1].

	Variable[2]	Type[3]	Unit[4]	Gmean	b	r^2	p
Gait characteristics	SD	value	s	0.818±0.041	-0.062	0.69	<0.01
	SF	value	s^{-1}	1.225±0.041	0.094	0.70	<0.01
	SL	value	m	2.493±0.127	0.627	0.95	<0.01
	$StL_{forelimb}$	value	m	1.100±0.047	0.14	0.86	<0.01
	$StL_{hindlimb}$	value	m	0.989±0.044	0.152	0.87	<0.01
	$StD_{forelimb}$	value	%SD	44.2±0.8	-5.4	0.78	<0.01
	$StD_{hindlimb}$	value	%SD	39.7±1.6	-3.9	0.86	<0.01
	Suspension duration	value	%SD	5.5±0.6	4.2	0.76	<0.01
	IS	value	%HRW s	81.8±4.1	-6.2	0.69	<0.01
Vertical ground reaction forces	FG_{tot}: P	value	%HRW	190.7±5.2	17.2	0.73	<0.01
	$FG_{forelimb}$: P	value	%HRW	105.4±3.5	11.6	0.62	<0.01
	$FG_{hindlimb}$: P	value	%HRW	87.3±3.7	6.6	0.77	<0.01
Kinematic variables	Atlas	z-ROM	mm	85±11	-5	0.06	0.18
	T6	z-ROM	mm	63±10	7	0.20	0.02
	L3	z-ROM	mm	100±9	-3	0.05	0.24
	S3	z-ROM	mm	86±5	-10	0.40	<0.01
	Back flexion-extension angle (T6-L3-S3)	Smean	degree	167.5±6.0	-0.9	0.33	<0.01
	Back flexion-extension angle (T6-L3-S3)	ROM	degree	6.5±1.1	0.1	0.01	0.63
	Rider sacrum – saddle hind	z-ROM	mm	16±11	4	0.12	0.07
Saddle forces	FS_{front}	Smean	%RW	33.1±7.8	5.7	0.04	0.27
	FS_{mid}	Smean	%RW	41.3±2.5	-1.8	0.02	0.48
	FS_{hind}	Smean	%RW	25.6±5.9	-3.9	0.06	0.21
	FS_{tot}: M	value	%RW	23.8±9.5	-12.2	0.40	<0.01
	FS_{front}: at time of FS_{tot} M	value	%RW	13.6±6.1	-3.3	0.03	0.33
	FS_{mid}: at time of FS_{tot} M	value	%RW	7.1±3.4	-7.1	0.61	<0.01
	FS_{hind}: at time of FS_{tot} M	value	%RW	3.2±2.5	-1.8	0.22	0.01
	FS_{tot}: P	value	%RW	218.9±28.9	44.9	0.71	<0.01
	FS_{front}: at time of FS_{tot} P	value	%RW	62.6±14.2	19.9	0.16	0.03
	FS_{mid}: at time of FS_{tot} P	value	%RW	98.4±21.5	18.2	0.23	0.01
	FS_{hind}: at time of FS_{tot} P	value	%RW	57.8±15.9	6.7	0.03	0.37

[1] Gmean: group mean values (± inter-subject standard deviation) of 7 horses at a mean trotting velocity of 3.05±0.08 m/s; b: regression coefficient (slope) given as units/(m/s); r^2: coefficient of determination; p: probability of slope b.

[2] Variables: SD: stride duration; SF: stride frequency; SL: stride length; StL: stance length; StD: stance duration, IS: stride impulse; FG: vertical ground reaction force peak (P); FS: saddle force, of total saddle pressure mat (with minimum M and peak P, see Figure 3); FS_{front}, FS_{mid}, FS_{hind}: saddle forces in the frontal, mid and hind transversal saddle third; $FS_{(third)}$ at time of FS_{tot} M or P: force at the respective saddle third contributing to FS_{tot} M or P magnitude, respectively.

[3] Type: value: discrete value; Smean: stride mean; ROM: range of motion; x: co-ordinate (towards head of horse); z: co-ordinate (upwards).

[4] Units: %SD: time as percentage of SD; %HRW: standardised to horse and rider weight (100 N/N); %RW: standardised to rider weight (100 N/N).

the saddle forces. The velocity dependency was investigated only for small velocity changes (walk: 19%, trot: 14%) within the speed ranges of collected walk and trot, because deriving data of high quality and practical relevance took precedence over the exploration of the maximal possible speed range within the respective gait. The main emphasis was on: (1) the ability of the rider to maintain the defined head neck position of the horse, (2) the ability of the rider to coordinate his/her movement with the horse and (3) to ride in a correct seat in all speeds.

Walk

Increasing velocity simplified the multi-component profile of the FS_{tot} curve; the M3-P3 aspect became dominant, whereas the other amplitudes evened out. Considerable variations in the profile of the FS_{tot} between the horse-rider pairs were observed. In previous studies, two (Fruehwirth *et al.*, 2004; Winkelmayr *et al.*, 2006) and three (Von Peinen *et al.*, 2009) maxima in each half of the stride cycle were found at walk. It is also known that different surfaces influence certain stride characteristics (Buchner *et al.*, 1994); if this or the different walking velocities caused the differences in the walking saddle force profiles between the study reported here and the studies with only two maxima made on a sand surface, remains speculative.

The M3 and P3 components of FS_{tot} were caused by the alternating level difference between the horse's croup and withers. In accordance with studies by Clayton (1995) the ridden horses adapted to speed preferentially by increasing their SL and to a lesser extent by increasing SF. Horses achieved longer SL by increasing the pro-retraction angle and thus StL in fore- and hindlimbs to a similar extent. In the forehand the resulting absolute increase of ROM of the vertical amplitude at the withers however was small, mainly due to the concomitant increase in fore- and backwards z-rotation of the shoulders. In contrast, the vertical amplitude of the croup, moving in inverse phase, increased proportionally to the increasing StL of the hindlimbs, which accentuated the rocking motion of the horse's back.

At time of FS_{tot} M3, when the respective front limb was in mid-stance and the hindlimbs in double-support, the periodical upward movement of the withers had reached a maximum and the sacrum dropped to its lowest position. Due to inertial influence, FS_{tot} M3 amounted on average to 86 %RW and was not equally distributed among the transversal sections of the saddle. Compared to the respective Smean, FS_{front} experienced the greatest reduction (-11.4 %RW), whereas FS_{hind} emerged an obviously smaller one (-1.9 %RW). At the walk the head moves in phase with the horse's croup and at time of FS_{tot} M3 the head was at its lowest position with the spinous processes of the withers presumably maximally upright. This assumption was supported by the observation that the horizontal distance between the front part of the saddle and the withers was maximal, leading to dominant weight reduction being focused at the frontal saddle parts. It occurred equally on both saddle sides due to the 'neutral', un-rotated, shoulder position at midstance. Simultaneously, the seat of the rider moved back towards the rear saddle parts and the vertical distance between rider's seat and cantle was maximal, unloading also the rear saddle parts. With increasing velocity, this rocking motion increased in frequency and amplitude. Consequently the above described relationships were more accentuated, leading to a velocity induced decrease at FS_{front} of -18.2 %RW per m/s at time of FS_{tot} M3 and a concurrent decrease of half that size occurring at FS_{hind}. Horses with the greatest increase in hindlimb StL, and thus with the most accentuated rocking movement, showed the greatest decrease of FS_{tot} M3 confirming this causative relationship.

The velocity dependent increase of FS_{tot} P3 (+34.0 %RW/(m/s)) was more distinct than the decrease of FS_{tot} M3 (-26.1 %RW/(m/s)). Two different events contributed to P3 which occurred in the diagonal stance phase at the end of each half cycle, solely on side of the protracting forelimb. Firstly, during forelimb protraction, the proximal part of the scapula rotated backwards and the neck elevated upwards. The muscles which are functionally active (Licka *et al.*, 2009) lie underneath the rigid head plate of the saddle and generate a unilateral pressure (Von Peinen *et al.*, 2009). Due to greater and faster protraction of the forelimb with increasing velocity and a larger ROM of the head/neck segment, muscle tension and diameter are supposed to increase more prominently, leading to an increase of FS_{front} at the time of FS_{tot} P3). Secondly, a comparable extent of the unilaterally generated FS_{tot} P3 originated from the central saddle section. At this time, the croup moves upwards and the hip on the side of the protracting forelimb is maximally rotated (z) upwards, whereas the rider still moves downwards. The known velocity-driven increase of the rocking back movement leads to an increase of counteracting forces in the centre of the saddle.

Trot

The movements of the rider at trot can largely be explained from the vertical and horizontal de- and acceleration of the horse's trunk (Byström *et al.*, 2009). Adaptation to higher trotting velocities was predominately made by increased SL which was achieved by enlarged StL but also by the increasing suspension duration, what increased the vertical dynamics of the gait. In the present study, mainly those variables changed, which related to the vertical movement of horse and rider.

With increasing velocity, FS_{tot} M decreased to a lesser extent than FS_{tot} P increased. At time of FS_{tot} P, mainly the load in the mid-section of the pressure mat increased. Despite a more dynamic movement of horse and rider and therefore increased FG peaks in fore- and hindlimbs as well as FS_{tot} P, ROM of back flexion-extension remained unchanged indicating a stiffening of the backline with increasing velocity. This parallels the findings of Robert *et al.* (2001a, 2002) who reported in unridden horses a decreased back flexion-extension movement with increasing speed. The EMG activities in *M. longissimus dorsi* and *M. rectus abdominis* increased at higher velocities within a speed range of 3.5-6.0 m/s (Robert *et al.*, 2001a, b). Denoix *et al.* (2001) ascertain that a higher activity of the *M. rectus abdominis* limits the passive thoracolumbar extension induced by the visceral mass acceleration and that the *M. longissimus dorsi* activity induces lumbosacral extension, facilitating hindlimb propulsion and stabilisation of the thoracolumbar spine. The increase in FG peak together with the higher stabilising muscle tension of the horses back explain the increase in counteracting forces between horse and rider (FS_{tot} P +44.9 %RW/(m/s)) at the trot. The velocity dependencies of temporal and force variables are in accordance with those reported by Weishaupt *et al.*

(2010) although that study investigated unridden horses at a larger speed range.

5. Conclusions

At walk, the accentuated rocking type of movement of the backline with increasing speed had the greatest effect on saddle forces. At trot the alterations in the saddle forces with increasing speed were mainly influenced by the vertical oscillation of horse and rider, the resulting higher ground reaction force peaks and the stiffening of the horse's back which led to an increase of the counteracting forces between the horse and the rider. Extremes and distribution of the saddle forces change obviously even within a small speed range. Data revealed that a 10% increase within the indicated speed range resulted in +5% (walk) and +14% (trot) higher total saddle force peaks.

Comparison of saddle forces of repeated saddle pressure measurements in the same horse, as well as between different horses, is only reliable with speed-matched data. This is essential in biomechanical research trials. Further, it has also to be taken into account under clinical conditions, when evaluating saddle fit pre and post saddle adjustment, or comparing different saddles on the same horse. In daily practice a speed measurement is not mandatory, but the rider as well as the clinician evaluating the saddle pressure measurement should pay attention of the horse moving or being ridden in the same manner.

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